

THE EFFECTS OF KNOWLEDGE CAPITAL ON ENHANCING FIRMS' PRODUCTIVITY IN TAIWAN: DOES R&D OR TECHNOLOGY IMPORT MATTER?*

JONG-RONG CHEN

*Graduate Institute of Industrial Economics, National Central University
Jhongli 320, Taiwan
jrchen@cc.ncu.edu.tw*

AND

CHIH-HAI YANG**

*Department of Economics, National Central University
Jhongli 320, Taiwan
chyang@mgt.ncu.edu.tw*

Received September 2005; Accepted February 2006

Abstract

Aside from R&D capital, acquiring technologies directly from abroad is also an important way to accumulate knowledge capital for both newly-industrialized economies (NIEs) and developing countries. Technology imports thus should play as an alternative vital source to enhance firms' productivity. Using firm-level panel data on Taiwan's manufacturing, our empirical study shows that R&D capital indeed has a significantly positive impact on productivity as with the case for advanced countries. The external technological source, technology imports, also contributes significantly to the productivity level and growth for Taiwanese firms, and it seems to matter relatively more than firms' R&D expenditures do. Moreover, the R&D spillover effect is found to influence productivity significantly.

Keywords: R&D, technology imports, productivity, spillover

JEL classification: O47

* This research has benefited from helpful comments by Lee Branstetter, participants at the 28th EARIE conference in Dublin, and anonymous referees. Financial Support provided by Taiwan National Science Council through grant NSC 89-2415-H-008-007 and by the Ministry of Education program for promoting academic excellence of universities under grant number 91-H-FA07-1-4-A3 is gratefully acknowledged. We are solely responsible for errors or opinions expressed.

** Corresponding Author.

I. *Introduction*

The story of Taiwan's postwar economic miracle by now is a very familiar one. Over the past decades, one of the most prominent factors influencing Taiwan's economic development has been the growing importance ascribed to its ability to raise the level of technological capability. Following the industry development model of OEM (original equipment manufacturer), Taiwanese firms produce goods under contracts for multinational corporations, which then market the resulting product under their own brand names. Taiwanese firms have learned and adopted foreign technologies to improve technological capabilities, which have been gradually associated with low-tech, imitative behaviors, for a long time. This means that these firms do not have to shoulder the burden of high marketing and R&D expenses.

It should not be inferred from mentioned above that there is no active research and development (R&D) or innovations taking place in Taiwan. Far from being so, as in fact the government ever since the early 1980s has undertaken several measures to actively support industrial R&D, aiming to improve firms' technological capabilities to meet the challenge of global competition in the current high-tech era. Indeed, we have seen a surge of innovative activities by both private and public sectors in Taiwan over the past couple decades. It is obvious from government statistics that Taiwanese firms have been enthusiastic users of foreign technologies, yet it is also clear that, particularly in the last decade, there has been an increasing tendency for them to spend reasonably large amounts of outlays for R&D efforts. Up until now, Taiwanese firms have been successful in closing the technological gap between them and their counterparts in developed countries, especially in the electronics industry. This achievement can also be verified by the output of innovation. Taiwanese firms' patenting has grown extremely fast both domestically and in the U.S. A study of "influential patenting" by the technology consulting firm CHI, Inc., placed Taiwan 4th in the world in terms of the quantity of its U.S. patents in 2000. Though it ranked well below the U.S. and Japan, it was well above such advanced G7 and European nations as Italy, Sweden, and the Netherlands.¹

Given this record of development, it is indisputable that Taiwanese firms have been very successful in narrowing the technological gap between them and their counterparts in the leading countries. It is also clear that this achievement is quite rare in the developing world and it has almost uniformly failed to happen outside of Asia and even within Asia. However, what is less well understood is how these firms have closed the gap and what lessons there may be in Taiwan's experience for other developing countries.

Despite such outstanding performance, whether Taiwan has moved along the correct direction of setting up its own technological capability is a debatable and crucial issue. There have been considerable debates and research studies concerning the best way to promote the development of technological capabilities for Taiwan.² To what extent should a country rely principally on its own R&D efforts versus relying primarily on technology imports? How does this optimal mix change accompanied by a country's development? These questions are very much in the minds of Taiwan's economic policymakers, as they themselves have sought to encourage the development of domestic technological capability. This study aims to quantify

¹ An international comparison of patents granted in the U.S. can be found in Trajtenberg (2001).

² For example, see Schive (1995).

the impact of R&D spending and technology imports on the productivity level and growth of Taiwanese firms at the micro level from 1990 to 1997.

Although a large number of studies have assessed the contribution of knowledge capital to productivity at the firm level using panel data and several studies have examined the influence of R&D spillovers on productivity, most of these studies focus on manufacturing firms in developed economies, such as the U.S., France, and Japan.³ Griffith *et al.* (2003) made an important contribution which develop a microeconomic foundation (industry-level) for the reduced-form equations on productivity growth that incorporates technology transfer as a key source for non-technological frontier countries, while empirical studies investigating the effect of technology imports on productivity for developing countries are quite limited. The effective balance between in-house R&D and technology imports and the interaction between these two strategies has however remained relatively less explored and has been hampered by a lack of adequate data.

Ferrantino (1992) and Bassant and Fikkert (1996) explored the effects of in-house R&D and technology purchases on productivity for Indian firms and found that both of them have a significantly positive impact on productivity. Ray and Bhaduri (2001) further emphasized the role of technology imports in determining research outputs for Indian firms. Based on aggregate data, Zhao (1995) analyzed the pattern of technology imports and their influences on China's indigenous technology. He indicated that imported technology has significantly enhanced China's technological build-up. Given the limited amount of literature, especially studies on the newly industrialized economies (NIEs), this paper aims to estimate the impacts of R&D capital and technology imports on firms' productivity level and growth in Taiwan.

The remainder of this paper is organized as follows. In section 2 we review the innovative activities of Taiwan in the 1990s. The empirical framework and estimation techniques are presented in section 3. Section 4 describes the dataset used for the empirical analysis. Section 5 reports the econometric results for the effects of knowledge capital, including R&D and technology imports on firms' productivity. Conclusions and policy implications are presented in the final section.

II. *In-house R&D versus Technology Imports in Taiwan, the 1990s*

Before plugging the micro data into this econometric analysis, we review recent trends in aggregate and industry-level innovation data.

In order to promote the technological capability for a non-developed country, it can be developed internally and/or acquired externally. Internal technological sources include in-house R&D activities and technology diffusion, while external sources include either technologies transferred from foreign direct investment (FDI) or technology imported directly from foreign firms. Both internal and external sources have their advantages and disadvantages. An internal source could impact proprietary technologies, which it could be risky and time-consuming. In contrast, an external source offers immediate access to desirable technologies, but it usually comes with certain restrictions and could eventually end up as a sort of technological reliance.

³ Examples include Hall and Mairesse (1995), Mairesse and Hall (1996), and Nakamura (2001).

TABLE 1. R&D AND TECHNOLOGY IMPORT OF TAIWAN (1988-1999)

	(1) R&D (million NT\$)	(2) Private Sector share(%)	(3) R&D/GNP (%)	(4) TI (million NT\$)	(5) TI/GNP (%)	(6) TI/RD (%)
1990	71548	54.2	1.62	12297	0.278	17.19
1991	81765	47.9	1.66	13015	0.264	15.92
1992	94828	47.8	1.74	13733	0.252	14.48
1993	103617	50.5	1.74	13684	0.230	13.21
1994	114682	51.8	1.78	14513	0.225	12.65
1995	125031	55.3	1.79	18240	0.261	14.59
1996	137955	57.3	1.83	25329	0.336	18.36
1997	156321	59.2	1.91	32417	0.396	20.74
1998	176455	61.7	1.96	38910	0.432	22.05
1999	190520	62.1	2.03	39003	0.416	20.47

Data source: Indicators of Science and Technology, Taiwan, 2001.

Note: TI means technology imports, which include technology licensing, technological cooperation, and technology instruction. The TI data of 1991 and 1996 are estimated due to the lack of TI data offered by the Industrial Statistical Report of Ministry of Economic Affairs when the national industrial and commercial survey was conducted in 1991 and 1996.

Table 1 displays Taiwan's R&D and technology imports in the 1990s. The second and third columns show the trends in aggregate R&D spending and the share of private sectors, respectively. They represent the internal source of technology development. The amount of R&D expenditure has increased more than two and half times — that is, from NT\$ 71.548 billion in 1990 to NT\$ 190.520 billion in 1999. The increasing trend of R&D expenditure shows the great effort for scientific and technological development in Taiwan, which is needed for industrial upgrading. At the same time, much of the recent increase came from the private sector. The share of private sector in R&D expenditure as a percentage of total R&D expenditure also rose steadily from 54.2% to 64.1%, meaning that there has been an accelerating tendency for Taiwanese firms to spend reasonably large amounts of money on their own R&D efforts. Accordingly, the ratio of R&D spending to GNP went from 1.62% in 1990 to 2.04% in 1999. Although it is still lower than that of developed countries, it still shows an increasing trend, in contrast to the decreasing or stable path in some developed countries.⁴

Columns (4) and (5) show the trend in aggregate technology imports, revealing the sum of money spent by Taiwanese firms on technology licensing and technical training by foreign experts. It serves as an important channel for firms to obtain advanced technologies. The sum of money spent on technology imports has increased steadily and remained large, though it was relatively lower than the expenditure on domestic R&D. The expenditure has increased more than three-fold, from NT\$ 12.297 billions in 1990 to NT\$ 39.003 billions in 1999, while its share of GNP declined lightly from 0.278% in 1990 to 0.225% in 1994, but has grown rapidly since 1995.

There are other points worth noting. First, the aggregate level data seems to reveal that a complementary relationship, rather than one of substitution, exists between domestic R&D

⁴ For example, the ratio of R&D expenditure to GNP is 2.15%, 2.11%, 2.02%, and 1.94%, respectively from 1993 to 1996 in the U.K.

expenditure and technology imports. Tan and Hwang (2002) presented quantitative evidence on this relationship for electronics firms in Taiwan. It means that both domestic investments in R&D and learning from abroad can accelerate the upgrading of industries' technological capabilities. Second, the amount of R&D spending is much greater than that of technology imports during the period under consideration.⁵ Column (6) displays the ratio of technology imports to R&D expenditures and it is found that the ratio hovers around 20%, revealing that Taiwanese firms rely more heavily on in-house R&D to raise their technological capabilities. Does the rapid increase in R&D spending in recent years imply that Taiwan should emphasize more on an internal technological source?

III. Empirical Framework and Estimation Procedures

1. Model Construction

The empirical framework that we use to measure the contribution of R&D and technology imports to productivity follows the standard approach in analyzing the contribution of R&D to productivity (Griliches and Mairesse, 1984; Cuneo and Mairesse, 1984; Griliches, 1986; Hall and Mairesse, 1995; Mairesse and Hall, 1996). We assume that the production function can be approximated by an augmented Cobb-Douglas function:

$$Y_{it} = A e^{\lambda t} C_{it}^{\alpha} L_{it}^{\beta} K_{it}^{\gamma} e^{\varepsilon_{it}} \quad (1)$$

where Y is output, C is fixed capital, L is labor input, and K is knowledge capital that consists of the firms' own R&D stock (R) and the stock of technology imports (T).⁶ The output effect of knowledge capital may potentially have time lags, implying that the time lags of knowledge capital should be included in this model. Because the lag structure is very poorly identified, we therefore adopt the standard approach of "stock" measure for the knowledge capital. The subscripts i and t refer to the firm i and the current year t . Term λ is the rate of disembodied exogenous technical change and ε is the error term reflecting the effects of unknown factors and other disturbances. If the decisions on R&D expenditure and technology imports are independent, then equation (1) can be written as:

$$Y_{it} = A e^{\lambda t} C_{it}^{\alpha} L_{it}^{\beta} R_{it}^{\phi} T_{it}^{\gamma} e^{\varepsilon_{it}} \quad (2)$$

To implement the estimation of the Cobb-Douglas function, we take logarithms and obtain the linear regression equation shown as below:

$$y_{it} = a + \lambda_t + \alpha c_{it} + \beta l_{it} + \phi r_{it} + \gamma t_{it} + \varepsilon_{it} \quad (3)$$

Here, ε is a multiplicative disturbance. Terms α , β , and especially ϕ and γ , are the parameters of our concern.

The decisions on importing advanced technologies and being devoted to R&D for firms are perhaps influenced interactively, and this relationship could be a substitute or comple-

⁵ In fact, the amount of R&D spending is also greater than the sum of different external technological sources, FDI, and technology imports.

⁶ Technology imports include the expense of technology licensing and technology instruction.

ment.⁷ Thus, the knowledge capital K_{it} should be a function that includes the stock of the accumulated past R&D investments, and the stock of technology purchased from advanced countries. A firm's productivity perhaps is influenced by the R&D of technological neighbors, and firms are shown to adjust the technological composition of their R&D in response to a technological opportunity (Jaffe, 1986). Hence, the exogenous variations of spillover can influence the decision of firms' R&D and then have an impact on productivity. When the effect of knowledge spillover to firm i from external sources is taken into account, it is partly determined by firms and serves as an endogenous variable (Adams, 2000). We can write the expression for K_{it} as follows:⁸

$$K_{it} = f(KRD_{it}, KTI_{it}, KSP_{it}) \quad (4)$$

where KRD_{it} is the stock of R&D capital, KTI_{it} is the stock of external technical knowledge generated by firm i through technology imports, and KSP_{it} is the stock of R&D spillover emanating from other firms in the same industry.⁹

Since each of these elements interacts with one another and these interactive effects are unknown, a specific function form for K_{it} is needed. We modify equation (1) as the following form:

$$Y_{it} = A e^{\lambda t} C_{it}^{\alpha} L_{it}^{\beta} e^{K_{it}} e^{\varepsilon_{it}} \quad (5)$$

where K_{it} takes the Generalized Leontief-linear functional form as:

$$\begin{aligned} K_{it} = & \gamma_R \sqrt{KRD_{it}} + \gamma_T \sqrt{KTI_{it}} + \gamma_S \sqrt{KSP_{it}} + \gamma_{RT} \sqrt{KRD_{it}} \sqrt{KTI_{it}} \\ & + \gamma_{RS} \sqrt{KRD_{it}} \sqrt{KSP_{it}} + \gamma_{TS} \sqrt{KTI_{it}} \sqrt{KSP_{it}} \end{aligned} \quad (6)$$

This specification has two advantages: it permits KRD_{it} , KTI_{it} , and KSP_{it} to be complements or substitutes to one another. Secondly, it avoids the problem of taking logarithms when R&D and technology imports are zero owing to firms not being involved in these innovative activities.¹⁰

Substituting equation (6) into equation (5) and then taking a logarithm gives us

$$\begin{aligned} y_{it} = & a + \lambda_t + \alpha c_{it} + \beta l_{it} + \gamma_R \sqrt{KRD_{it}} + \gamma_T \sqrt{KTI_{it}} + \gamma_S \sqrt{KSP_{it}} \\ & + \gamma_{RT} \sqrt{KRD_{it}} \sqrt{KTI_{it}} + \gamma_{RS} \sqrt{KRD_{it}} \sqrt{KSP_{it}} + \gamma_{TS} \sqrt{KTI_{it}} \sqrt{KSP_{it}} + \varepsilon_{it} \end{aligned} \quad (7)$$

Under the situation that excludes the spillover effect, the equation estimated can be written as:

$$y_{it} = a + \lambda_t + \alpha c_{it} + \beta l_{it} + \gamma_R \sqrt{KRD_{it}} + \gamma_T \sqrt{KTI_{it}} + \gamma_{RT} \sqrt{KRD_{it}} \sqrt{KTI_{it}} + \varepsilon_{it} \quad (8)$$

Equations (7) and (8), the two versions of the general specifications, will be explored in this study. In addition, the specification of equation (3) will also be estimated in our study for comparison.

⁷ See Katrak (1985, 1997), Lee (1996), and Tan and Hwang (2002).

⁸ See Fuss et al (1978).

⁹ We do not consider, in this formulation, technology transferred via FDI in Taiwan. Moreover, innovation in purchased intermediate products contributing to increased value added (rent spillover) is also not considered in this paper. This may be a serious omission, which we hope to examine in a future study.

¹⁰ There are also disadvantages in this specification, please see Basant and Fikkert (1996).

2. Estimation Techniques

On exploring the relationship between knowledge capital and productivity, as is common with panel data, we allow for the existence of individual effects which are potentially correlated with the right-hand side regressors, such that:

$$\varepsilon_{it} = v_{it} + u_i \quad (9)$$

Here u_i is a firm fixed effect that corresponds to the permanent, unobserved heterogeneity across firms, but not within a firm over time, and v_{it} is a "white noise" error term, representing a period-specific shock for firm i , and it is assumed to be independent across firms and over time. Using a "within firm" panel estimator, the fixed effect (FE) or the random effect (RE) technique, to eliminate the individual effect is a standard estimation method. As is well known, FE is less efficient than RE, because it uses only a variation in the data within each firm through time (Hsiao, 1986). However, this firm-specific component in the error term may be quite plausibly correlated with a firm's knowledge capital, implying that the RE estimators are inconsistent when the assumption of zero correlation between the error term and right-hand side regressors is violated. Therefore, results from both RE and FE specifications are provided, accompanying the statistics of Hausman tests.

If there are measurement errors in the variables, then there will be a serious bias in the within estimate. Under a variety of assumptions, this error also tends to bias the first-difference (growth rate) coefficient (Griliches and Hausman, 1986). In order to get robust estimates for the standard errors when measurement errors appear and to explore the relationship between knowledge and productivity growth, this bias should be reduced. We thus employ a within-firm estimate obtained by the Generalized Method of Moments (GMM) approach developed by Arellano and Bond (1991), Keane and Runkle (1992), and Ahn and Schmidt (1992). Using the setting of linear regression models with predetermined rather than exogenous right-hand side variables, GMM proves to be better, because it is robust in the presence of heteroscedasticity across firms and in correlation of the disturbances within firms over time. It can also be efficient even under a weak assumption on the disturbance.¹¹ This approach sets up a series of successively stronger orthogonality conditions that are valid under various versions of the panel data models and choose among these specifications according to the results of GMM estimations on these conditions.

To be more precise, we rewrite equation (3) as:¹²

$$y_{it} = \beta x_{it} + u_{it} = \beta x_{it} + \alpha_i + \varepsilon_{it} \quad i = 1, \dots, N; t = \xi + 1, \dots, T \quad (10)$$

There are ξ periods of data available as instruments for the first period of estimation. Term β is the parameter of interest, and α_i is the firm fixed effect which is potentially correlated with x_{it} . Therefore, its first difference is:

$$\Delta u_{it} = \Delta y_{it} - \beta \Delta x_{it} \quad (11)$$

Here independent variables x are predetermined rather than exogenous. Assume I to be the

¹¹ There is of course some cost of this flexibility; see Arellano and Bond (1991).

¹² The time dummy is deleted in equation (12). Even so, the estimate of the linear panel data model is consistent and efficient. See Mairesse and Hall (1996).

vector of instrumental variables, which are then defined:

$$\Delta u_i = (\Delta u_{i\tau+1}, \Delta u_{i\tau+2}, \dots, \Delta u_{iT}) \text{ and } I_i = (I_i^{(1)}, I_i^{(2)}, \dots, I_i^{(m)})$$

where

$$I_i^{(m)} = (I_{i,T-\tau+1}^{(m)}, I_{i,T-\tau+2}^{(m)}, \dots, I_{i,0}^{(m)}, I_{i,1}^{(m)}, \dots, I_{i,T}^{(m)}) \text{ for all } m$$

There are mT' and T component factors in I_i and Δu_i . Assume I to be a valid instrument, and then the sample equivalents of these moment conditions are:

$$f_i(\beta) = \Delta u_i \otimes I_i \quad (12)$$

The GMM estimators of β minimize the quantity:

$$\phi(\beta) = \left[\frac{1}{N} \sum_{i=1}^N f_i(\beta) \right] W \left[\frac{1}{N} \sum_{i=1}^N f_i(\beta) \right]' \quad (13)$$

with respect to β , where W is a positive definite symmetric matrix. If W can be chosen as a consistent estimate of the inverse of the covariance matrix Ω of $f(\beta)$, then the estimator is consistent and asymptotically efficient.¹³

IV. Variable Construction and Data

In the formulation of equations (3), (7), and (8), y denotes a value-added output concept. Since materials are not included in the model, we thus use value-added (VA) as the dependent variable. The value-added is defined as the sale minus materials which include the intermediate inputs, fuel, and electricity and which are deflated by the annual inflation rate. As for the independent variables, our measure of capital stock (C) is a constructed estimate of equipment and plant adjusted for inflation. Conceptually, capital and labor measures used to estimate should be purged of the contribution of R&D inputs, otherwise, the cross section estimates are not necessarily incorrect, but do induce an “excess” R&D elasticity (Mairesse and Hall, 1996). Owing to the lack of detailed R&D information for capital and labor input data, we cannot correct for these inputs. Our measure of labor (L) is thus the average number of workers during that year.

In constructing the knowledge capital, we adopt not only the R&D stock (KRD) that is used in previous studies, but also an external technological source of knowledge capital, whereby the stock of technology imports (KTI) is indexed as knowledge capital. The expenditure of firms on disembodied technologies through licensing agreements and technology instructors is another important factor to improve the technological capability. For comparing their contributions to productivity for Taiwanese firms, our measurements of R&D capital and stock of technology imports follow that in Hall (1990), using a perpetual inventory method and defining the equation of knowledge capital K as follows:

$$K_t = R_t + (1 - \delta)R_{t-1} + (1 - \delta)^2 R_{t-2} + \dots \quad (14)$$

where K represents the R&D stock and stock of technology imports, and R is the R&D

¹³ Even if W is inconsistent, the estimator of β is consistent under fairly general conditions. See Hansen (1982).

expenditure or technology imports in each period. Term δ denotes the depreciation rate.

Since the study period covers eight years, up to two lagged years of R&D and technology imports are employed to construct the knowledge capital stock K .¹⁴ The R&D stock is constructed from past R&D flow, at a constant depreciation rate of 15% per year.¹⁵ Similarly, the stock of technology imports is constructed from the past history of technology imports, with a constant depreciation rate of 15%.¹⁶

Concerning the spillover effect, there are several constructive ways employed in the literature.¹⁷ We use the simplest measure that includes the sum of R&D or technology imports conducted by firms other than firm i in firm i 's industry, which is:

$$SP_i = \sum_{j \neq i}^n w_j KC_j \quad (15)$$

where term SP_i denotes the spillover effect of firm i that benefits from other firms within the industry. Term w is the weight matrix, and KC denotes knowledge capital, measured by R&D or technology imports. For simplicity, we assume the same weight for every firm in that $w = 1$ and then we construct the spillover stock, KSP_{it} , for firm i by applying the perpetual method as equation (14). The spillover effect is measured as the R&D conducted by Taiwanese firms other than firm i in firm i 's industry.

Data used in this study includes 279 manufacturing firms that were listed on the Taiwan Stock Exchange (TSE) from 1990 to 1997. This provides us with 8 years of balanced panel containing 2232 observations. Table 2 shows some of the characteristics of the samples. In industrial distribution, the first largest share is the electronics industry, and the second largest one is the textile industry. There are 56 electronics firms accounting for 20.1% of our sample. In fact, the electronics industry has become increasingly high-tech and has played an increasingly important role since 1980 in Taiwan. By 1980, electrical/electronics products accounted for a greater share of Taiwan's manufacturing value-added and exports than textile, and the electronics industry has continued to grow. By 1995, the electronics industry accounted for 23% of Taiwan's manufacturing GDP and over 35% of its exports.

To construct the knowledge capital, the data for R&D expenditures and technology imports stretching back to 1988 are collected. Therefore, the data of R&D expenditures and technology imports run from 1988 to 1997, and then we get a balanced 8-period panel of data.

¹⁴ According to perpetual inventory method, the R&D capital is constructed as $K_t = R_t + (1 - \delta)K_{t-1}$, and $K_1 = R_0 + (1 - \delta)R_{-1} + (1 - \delta)^2 R_{-2} + \dots = \sum_{i=0}^{\infty} R_{-i} (1 - \delta)^i = R_0 \sum_{i=0}^{\infty} [\frac{1 - \delta}{1 + g}]^i = \frac{R_1}{g + \delta}$, where g is the growth rate of R&D expenditure. This measure is described in Hall (1990), Hall and Mairesse (1995), and Mairesse and Hall (1996). Because electronics firms engaged in innovation activity with a higher R&D intensity and some of them were established after 1987 in our short 8-year panel, R&D capital constructed by perpetual inventory method may overestimate electronics firms' knowledge capital. Thus, it may be adequate to use only 2 lags to construct the variable. The same logic and method can also be found in Cuneo and Mairesse (1984).

¹⁵ All variables, excluding patent, are all deflated by a wholesale price index defined at the two-digit industry level for the base year of 1992.

¹⁶ The depreciation rate of R&D capital is usually assumed to be 15%. See, Mairesse and Hall (1996), Hall and Mairesse (1995), and Griliches and Mairesse (1990). As for the depreciation rate of technology imports, there is no previous study serving as a reference, and so we assume a 15% as the depreciation rate of R&D capital. Indeed, we have tried several depreciation rates of 0%, 10%, 15%, 20%, and 30% and there are similar results.

¹⁷ See Griliches (1992) for a survey.

TABLE 2. SAMPLE CHARACTERISTICS OF MANUFACTURING IN TAIWAN (1990-1997)

Industry	Number of Firms	Employment (persons)	R&D-Sales Ratio (%)	Average Number of Issued Taiwan Patents
Cement	8	772.8	0.053	0.078
Food	28	755.0	0.128	0.143
Plastics	17	1276.5	0.458	0.912
Textiles	49	1285.5	0.231	0.071
Electric & Machinery	20	1375.9	1.349	2.400
Electric Appliance & Cable	13	1285.5	0.550	2.058
Chemical	18	518.6	1.537	0.830
Glass Products & Ceramics	7	955.5	0.598	2.929
Paper & Pulp	7	1450.0	0.334	0.446
Steel & Iron	27	784.4	0.111	0.560
Rubber	8	912.2	0.849	5.563
Automobile	5	2673.0	1.055	2.000
Electronics	56	1053.6	2.344	7.114
Other Manufacturing	16	975.1	0.751	1.820
Total or Average	279	1071.2	0.895	2.224

Note: Employment, R&D to Sales, and Patents are the average from 1990 to 1997.

The samples are based primarily on the information contained in the data bank of Taiwan Economic Journal.

V. Empirical Results

1. Knowledge Capital and Productivity

Table 3 presents a series of conventional linear panel data estimations for equation (3), serving as the benchmark model.

The second column shows the regression estimated by pooling firms and the time for the period 1990-1997. It represents the estimates of a cross-sectional dimension. The third and fourth columns, whereby with overall firm means removed ($y_{it} - y_{i\cdot}$), yield the within-firm estimations. The within-firm estimations can be separated into a random effect model and a fixed effect model.

First, we discuss the estimates obtained from the benchmark model that assumes R&D and technology imports are independent and then make a comparison with previous studies based on developed countries. In the cross-sectional dimension, the labor coefficient is higher than that of the capital variable, and they both have a significant impact on productivity level. The question we concern with is does knowledge capital also has a significant impact on productivity in Taiwan? Similar to earlier studies, the parameter γ is of positive significance at the 1% statistical level, revealing that R&D capital indeed has a positive impact on the productivity level in Taiwan. - that is, firms devoting more R&D efforts have a better performance in terms of productivity. The estimated magnitude of R&D elasticity is 0.020. In the time serial dimension, the estimated R&D elasticity is 0.022 in the random effect model and 0.021 in the fixed effect model, and these coefficients are both statistically significant. Taiwan-

TABLE 3. R&D, TECHNOLOGY IMPORTS AND PRODUCTIVITY: BENCHMARK MODELS

	<i>Cross-Sectional (Pooling Estimates)</i>	<i>Within-firm (Random Effect)</i>	<i>Within-firm (Fixed Effect)</i>
Constant Term	6.457*** (0.147)	5.887*** (0.220)	
ln C	0.251*** (0.014)	0.294*** (0.021)	0.317*** (0.028)
ln L	0.624*** (0.021)	0.614*** (0.032)	0.628*** (0.047)
ln KRD	0.020*** (0.003)	0.022*** (0.004)	0.021*** (0.004)
ln KTI	0.018*** (0.005)	0.030*** (0.005)	0.034*** (0.006)
Hausman test			$\chi^2(4) = 8.992^*$
R ²	0.668	0.667	0.883

Note: The numbers in parentheses are standard errors. *** and * represent the 1% and 10% significant levels, respectively.

ese firms have been engaged more intensively in R&D since the 1980s, and so the impact of R&D capital on the productivity level is significant during our survey period from 1990 to 1997.

Griliches and Mairesse (1984) obtained 0.05 in cross-section and 0.09 in the within estimation using 133 U.S. firms from 1966 to 1977. Cuneo and Mairesse (1984) obtained 0.20 in the total and 0.05 in the within estimation on a sample of 182 French firms from 1972 to 1977. Mairesse and Hall (1996) obtained 0.090 in the total and 0.008 in the within estimation for the sale regression on French data, and 0.090 in the total and 0.041 in the within estimation on U.S. data from 1981 to 1989. Mairesse and Sassenou (1991) summarized the estimation of γ from nine studies conducted in developed countries based on firm-level data, where the estimated γ is between 0.05 and 0.21. Compared with those of advanced economies, the R&D coefficient is relatively lower than that of the U.S. and France in the 1970s and 1980s, but the magnitude of our within estimate approach is quite comparable with that of France in the 1980s (Mairesse and Hall, 1996). Despite the lower R&D elasticity, the positive impact of R&D capital on productivity implies that R&D is an important factor influencing economic development and raising the level of technology for Taiwan and perhaps for other developing countries.¹⁸

Although R&D has a significant positive impact on firms' productivity, is it the only way to promote productivity? How much do external technological sources affect a firm's productivity? From the viewpoint of policymakers of NICs, this is an important issue to be taken into consideration when formulating an industrial technology policy. The estimates of using technology imports to assess the contribution of knowledge to productivity show that the coefficient for $\log KTI$ is 0.018 in cross-section and hovers around 0.032 in the within estimation, in which both are highly significant at the 1% statistical level. As can be seen from these results, the same pattern is evident in that both R&D expenditure and technology imports are positively associated with a higher level of productivity. In comparison with the coefficients of R&D capital, the impact of the stock of technology imports is quite similar to

¹⁸ Because there is no other firm-level study using Taiwan data, we cannot find the time tendency of R&D contribution.

TABLE 4. R&D, TECHNOLOGY IMPORTS, AND PRODUCTIVITY LEVEL IN TAIWAN (1990-1997)

	(i) Cross-Sectional (Pooling Estimates)	(ii) Within-firm (Random Effect)	(iii) Within-firm (Fixed Effect)	(iv) Cross-Sectional (Pooling Estimates)	(v) Within-firm (Random Effect)	(vi) Within-firm (Fixed Effect)
Constant Term	6.961*** (0.150)	6.957*** (0.224)		6.917*** (0.163)	6.855*** (0.220)	
ln C	0.257*** (0.013)	0.273*** (0.020)	0.258*** (0.026)	0.256*** (0.014)	0.279*** (0.019)	0.203*** (0.025)
ln L	0.527*** (0.021)	0.477*** (0.032)	0.486*** (0.025)	0.550*** (0.021)	0.452*** (0.032)	0.403*** (0.043)
\sqrt{KRD}	0.909E-03*** (0.619E-04)	0.127E-02*** (0.786E-04)	0.148E-02*** (0.944E-04)	0.528E-03*** (0.100E-03)	0.773E-03*** (0.120E-03)	0.001*** (0.144E-03)
\sqrt{KTI}	0.003*** (0.761E-03)	0.006*** (0.866E-03)	0.008*** (0.975E-03)	0.002*** (0.901E-03)	0.004*** (0.001)	0.005*** (0.114E-02)
$\sqrt{KRD} \sqrt{KTI}$	-0.411E-05*** (0.101E-05)	-0.589E-05*** (0.933E-06)	-0.698E-05*** (0.100E-05)	-0.486E-05*** (0.104E-05)	-0.488E-05*** (0.900E-06)	-0.499E-05*** (0.895E-06)
\sqrt{KSP}				0.454E-04*** (0.170E-04)	0.172E-03*** (0.201E-04)	0.332E-03*** (0.259E-04)
$\sqrt{KRD} \sqrt{KSP}$				0.136E-06*** (0.303E-07)	0.237E-07 (0.296E-07)	-0.522E-07 (0.332E-07)
$\sqrt{KTI} \sqrt{KSP}$				0.756E-06** (0.341E-06)	0.304E-06 (0.300E-06)	0.577E-07 (0.316E-06)
Hausman test			$\chi^2(5) = 25.4^{***}$			$\chi^2(8) = 123^{***}$
R ²	0.692	0.685	0.894	0.697	0.656	0.906

Note: The numbers in parentheses are standard errors. *** and ** represent the 1% and 5% significant levels respectively.

that of $\log KRD$ in the cross estimation of the firm level in terms of magnitude. However, it is about one and half times larger than that in the within estimates. This means that both external and internal technological sources have quite a similar contribution to productivity level in the cross-sectional dimension, and technology imports appear to have a greater impact on firms' productivity in the period we survey.

Table 4 shows the estimates of equation (7) and (8). Columns (i) to (iii) display the regression results without the spillover effect. Compared with the regression results with a spillover effect shown in columns (iv) to (vi) of Table 4, the magnitude of coefficients for the capital and labor variables are quite similar in the cross-sectional and time series dimensions, and they all have a significant impact on productivity level. Knowledge capital, measured by R&D or technology imports, also has a significant impact on productivity. The coefficient of R&D stock is 0.127E-02 without and 0.773E-03 with the spillover effect in the RE regression, but the Hausman statistics reject the RE specification, and so we need to consider the FE estimates even though the RE specification may be preferred to FE in this issue (Mairesse and Sassenou, 1991). The FE estimates for the KRD coefficient, without and with the spillover effect, are higher than their RE counterparts, and the impact of R&D stock on productivity is still quite significant. A similar pattern presents for the stock of technology imports, which serves as the external source of knowledge. The coefficient of KTI in the FE regression is higher than that in RE estimates, and they are statistically significant. These results provide evidence that firms engage in innovative activities to raise their technology capability actively, devoting more R&D efforts or acquiring technologies abroad, and resulting in a better

productivity performance. As mentioned earlier, the coefficient of *KTI* is larger than that of *KRD* which implies that external technological sources may have a greater impact on firms' productivity than internal technological sources in the cross-sectional and time dimension of the 1990s.

The coefficient for the interaction effect between R&D stock and technology imports is negative and significant, implying that R&D and technology imports tend to be substitutes in the production of knowledge in the period we survey. This result contradicts the assertion of Tan and Hwang (2002) for Taiwanese electronics firms. One possible interpretation is that the relation might vary across industries, while the findings drawn from this study are obtained from a pool of data for all industries.

The other issue we investigate is whether there is a positive knowledge spillover effect on firms' productivity. The coefficients for the spillover variable reported in columns (iv) to (vi) are positive and significant at the 1% statistical level, while the interactive terms are significantly positive for cross-sectional estimates. Firms seem to be benefited from both the direct and indirect effects of knowledge spillover in the cross-sectional estimate. The direct spillover effect that consists of the R&D of each firm's competitors in the same industry also appears as a positive and significant impact on productivity in the within-firm estimate, whereas the interaction effect between spillover and R&D or technology imports seems quite small.

2. Knowledge Capital and Productivity Growth

To correct the potential measurement error in the variables we are interested and to investigate whether more knowledge capital induces a higher rate of productivity growth, both econometric techniques of first-difference and GMM are employed. Table 5 presents a series of estimations.¹⁹ The coefficients estimated can offer some information about the relationship between knowledge capital and productivity growth for Taiwanese firms during the 1990s.

In the traditional estimates for growth using the first-difference shown as columns (i) to (iii), the coefficients for labor and capital variables are positive and statistically significant, and the contribution of labor on productivity growth is larger than that of capital. However, the results of the GMM approach, which are robust in the presence of heteroscedasticity across firms and in correlation of the disturbances within firms over time, indicate that the impact of capital changes on productivity growth remains similar, whereas labor input has a higher excess contribution on firms' productivity growth on the estimates of columns (iv) to (vi).

The important issue is whether increased knowledge capital has a significant impact on productivity growth. The first difference estimates show that the "excess" productivity of R&D is positive, but not significant, in column (i). At the same time, the estimates in columns (ii) and (iii) show that the coefficients for *KRD* are significantly positive for the estimations of the general forms as equations (7) and (8). Alternatively, the more adequate estimates of the GMM approach in columns (iv) to (vi) reveal that most of the coefficients for R&D capital are significantly positive and the magnitude is about two times larger than that obtained from

¹⁹ In this GMM estimation, we use all lagged capital, R&D expenditures, and technology imports as instrumental variables. The chi-square values shown in Table 5 are statistics for testing the hypothesis of over-identification. All of the statistics do not reject the null hypothesis at a rigorous criterion of 1%.

TABLE 5. R&D, TECHNOLOGY IMPORTS, AND PRODUCTIVITY GROWTH IN TAIWAN (1990-1997)

	<i>First-difference</i>			<i>GMM</i>		
	(i)	(ii)	(iii)	(iv)	(v)	(iv)
Constant Term	0.032*** (0.004)	0.032*** (0.004)	0.024*** (0.005)			
$\Delta \ln C$	0.109*** (0.033)	0.096*** (0.032)	0.088*** (0.032)	0.096* (0.051)	0.140*** (0.049)	0.130** (0.041)
$\Delta \ln L$	0.234*** (0.052)	0.181*** (0.053)	0.176*** (0.053)	0.901*** (0.097)	0.618*** (0.079)	0.502*** (0.068)
$\Delta \ln KRD$	0.004 (0.005)			0.011** (0.005)		
$\Delta \ln KTI$	0.012* (0.007)			0.021*** (0.007)		
$\Delta \sqrt{KRD}$		0.517E-03*** (0.107E-03)	0.301E-03* (0.175E-03)		0.905E-03*** (0.695E-04)	0.129E-03 (0.181E-03)
$\Delta \sqrt{KTI}$		0.231E-02* (0.125E-02)	0.141E-02 (0.145E-02)		0.157E-02** (0.694E-03)	0.381E-02*** (0.136E-02)
$\Delta \sqrt{KRD} \sqrt{KTI}$		-0.283E-05** (0.137E-05)	-0.251E-05* (0.138E-05)		-0.267E-05* (0.763E-06)	-0.289E-05** (0.121E-05)
$\Delta \sqrt{KSP}$			0.462E-04 (0.321E-04)			0.162E-03*** (0.467E-04)
$\Delta \sqrt{KRD} \sqrt{KSP}$			0.237E-07 (0.381E-07)			0.108E-06** (0.495E-07)
$\Delta \sqrt{KTI} \sqrt{KSP}$			0.128E-06 (0.365E-06)			0.174E-05*** (0.362E-06)
Sargan test				$\chi^2(44) = 59.55$	$\chi^2(43) = 64.54$	$\chi^2(40) = 57.58$
R ²	0.309	0.356	0.376			

Note: The numbers in parentheses are standard errors. ***, **, and * represent the 1%, 5% and 10% significant levels, respectively.

the first difference estimation.

What the above implies is that firms with an increase on R&D investment have a higher productivity growth on average during the survey period. This is an encouraging result for Taiwan's government, which has all along encouraged firms to devote more efforts and resources to R&D. Hall (1993) found that, during the 1980s, the market values of U.S. firms undertaking R&D investments obtain no excess return from such investments. Mairesse and Hall (1996) agreed with the finding of Hall (1993) based on the results obtained from U.S. and French data of the 1980s. Compared with the experiences of advanced countries, our results indicate that more R&D investment induces a higher productivity growth for Taiwanese firms in the 1990s, implying that there still is an increasing return to R&D investment for Taiwan.

As for the impact of technology imports on productivity growth, the coefficient for $\Delta \ln STI$ is significant statistically in all of the first-difference estimations. In the GMM estimations, the coefficients are still positive and significant at a conventional statistical level and they show a larger impact than that obtained from the first difference estimation. Compared with R&D investments, the impact of technology imports on productivity growth is larger and ranges from 2 to 4 times that of R&D. This result is quite similar to when we explore the impact of knowledge on productivity level in the within estimation shown in Tables 3 and 4. One possible interpretation is as mentioned above whereby an external source can offer immediate access to desirable technologies and result in a higher rate of productivity

growth in the short run.

The GMM estimates in Table 5 indicate that both direct and indirect effects of spillover contribute a significant impact on productivity growth for Taiwanese firms in 1990s. This strong spillover effect perhaps arises, because many industries have a feature of an industry cluster in Taiwan.²⁰

In sum, our empirical results indicate that both R&D and technology imports have a positive impact on firms' productivity level and growth, implying that both in-house R&D and technologies imported directly from foreign firms are important driving forces to improve technological capabilities to meet the challenge of global competition. Whether this excess productivity will decline to zero, as is the case for advanced countries, deserves future study.

VI. *Conclusion and Policy Implications*

There are a large body of studies showing that knowledge capital, proxied by R&D capital has a positive impact on firms' productivity in developed countries, such as the U.S. and France. Can this be a lesson for developing economies or NICs? Aside from R&D capital, acquiring technologies directly from abroad is also an alternative method to accumulate knowledge capital for NICs and developing countries. Thus, what is the best way to promote technological development is a crucial and debatable issue. Moreover, to what extent should a country rely principally on its own technological efforts versus relying primarily on technology imports?

Based on a panel data of Taiwanese manufacturing firms, the empirical analyses show that knowledge capital does actually have a significant positive impact on productivity as in the case of advanced countries. The elasticity of R&D capital is about 0.020 and 0.022 in the cross-sectional and time-dimensional estimation, respectively. Despite the ongoing increase in R&D spending, which itself may reflect an increasing technological maturity on Taiwanese firms, technology imports still contribute to the productivity level and growth. The impact of technology imports on productivity is quite similar to that of R&D capital, and it seems to matter relatively more than firms' R&D expenditures in the estimates of the time dimension and growth.

As drawn from this study, do these results suggest that the external technological source is more important than in-house R&D for Taiwan? We cannot conclude yet the relative importance of R&D and technology imports, but it does deserve a further insightful investigation. This result suggests only that technology imports will continue to be a vital strategy for Taiwanese firms for years to come, especially considering the deep technological integration with research centers in the U.S. and Japan, which are the two major Pacific technological superpowers and major technology source countries of Taiwan. More R&D spending is also necessary for Taiwanese firms aiming to establish technological self-reliance,²¹ even though it may be a comparative disadvantage in the R&D race with leading countries. From a policy perspective, these results imply that tax incentives, financial assistance, R&D grants, and other

²⁰ The clustering phenomenon can be seen in the bicycle industry (Chu, 1997), the tool machine industry (Amsden, 1985), and the electronics industry (Chen, 2002), for example.

²¹ According to Katrak (1985), one necessary condition of technological self-reliance is that the growth rate of R&D expenditure must be larger than that of technology imports.

measures used to promote R&D spending by the government should be considered to encourage importing advanced technologies for the purpose of promoting technological development.

REFERENCES

- Adams, J.D. (2000), Endogenous R&D Spillovers and Industrial Research Productivity, *NBER Working Paper*, No. 7484.
- Ahn, S.C. and P. Schmidt (1992), Efficient Estimation of Panel Data with Exogenous and Lagged Dependent Regressors, *Journal of Econometrics*, 68, pp.5-27.
- Amsden, A.H. (1985), The Division of Labour is Limited by the Rate of Growth of the Market: the Taiwan Machine Tool Industry in the 1970s, *Cambridge Journal of Economics*, 9, pp.271-284.
- Arellano, M. and S. Bond (1991), Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations, *Review of Economic Studies*, 58, pp.277-297.
- Basant, R. and B. Fikkert (1996), The Effects of R&D, Foreign Technology Purchase, and Domestic and International Spillovers on Productivity in Indian Firms. *Review of Economics and Statistics*, 78, pp.187-199.
- Chen, S.H. (2002), Global Production Networks and Information Technology: The Case of Taiwan, *Industry and Innovation*, 9(3), pp.249-265.
- Chu, W.W. (1997), Causes of Growth: A Study of Taiwan's Bicycle Industry, *Cambridge Journal of Economics*, 21, pp.55-72.
- Cuneo, P. and J. Mairesse (1984), Productivity and R&D at the Firm Level in French Manufacturing, in Z. Griliches, ed., *R&D, Patents, and Productivity*, University of Chicago Press, Chicago, IL.
- Ferrantino, M.J. (1992), Technology Expenditures, Factor Intensity, and Efficiency in Indian Manufacturing, *Review of Economics and Statistics*, 74, pp.689-700.
- Fuss, M, D. McFadden and Y. Mundlak (1978), A Survey of Functional Forms in the Economic Analysis of Production, in M. Fuss and D. McFadden (eds.) *Production Economics: A Dual Approach to Theory and Application*, Vol. 1, (Amsterdam: North-Holland), pp.219-268.
- Griffith, R., S. Redding and J. Van Reenen (2003), R&D and Absorptive Capacity: Theory and Empirical Evidence, *Scandinavian Journal of Economics*, 105, pp.99-118.
- Griliches, Z. (1986), Productivity, R&D, and Basic Research at the Firm Level in the 1970s, *American Economic review*, 76, pp.141-154.
- Griliches, Z. (1992), The Search for R&D Spillovers, *Scandinavian Journal of Economics*, 94, Supplement, S29-S47.
- Griliches, Z. and J. Mairesse (1984), Productivity and R&D at the Firm Level, in Z. Griliches, ed., *R&D, Patents, and Productivity*, University of Chicago Press, Chicago, IL.
- Hall, B.H. (1990), The Manufacturing Sector Master File: 1959-1987, *NBER Working Paper* No.3366, Cambridge, Mass.
- Hall, B. (1993), "Industrial Research During 1980s: Did Rate of Return Fall?" *Brookings Papers on Economic Activity*. Micro Economics (2), Washington D.C.

- Hall, B.H. and J. Mairesse (1995), Exploring the Relationship between R&D and Productivity in France Manufacturing Firms, *Journal of Econometrics*, 65, pp.263-293.
- Hansen, L.P. (1982), Large Sample Properties of Methods of Moment Estimators, *Econometrica*, 50, pp.1029-1054.
- Hsiao, C. (1986), *Analysis of Panel Data*, Cambridge University Press.
- Jaffe, A.B. (1986), Technological Opportunity and spillovers of R&D: Evidence from Firms' Patent, Profits, and Market Value, *American Economics Review*, 76, pp.984-1001.
- Katrak, H. (1985), Imported Technology, Enterprise Size and R&D in a Newly Industrialized Country: The Indian Experience, *Oxford Bulletin of Economics and Statistics*, 47, pp.213-229.
- Katrak, H. (1997), Developing Countries' Imports of Technology, In-House Technological Capabilities and Efforts: An Analysis of Indian Experience, *Journal of Development Economics*, 53, pp.67-83.
- Keane, M.P. and D.E. Runkle (1992), On the Estimation of Panel Data Models with Serial Correlation When Instruments Are Not Strictly Exogenous, *Journal of Economics and Statistics*, 10, pp.1-29.
- Lee, J. (1996), Technology Imports and R&D Efforts of Korean Manufacturing Firms, *Journal of Development Economics*, 50, pp.197-201.
- Mairesse, J. and B.H. Hall (1996), Estimating the Productivity of Research and Development in France and United States Manufacturing Firms: An Exploration of Simultaneity Issues with GMM, in Wagner K., and B. van Ark, eds., *International Productivity Comparisons* (Amsterdam, North-Holland), pp.285-315.
- Mairesse, J. and M. Sassenou (1991), R&D and Productivity: A Survey of Econometric Studies at the Firm Level, *Science-Technology Industry Review*, 8, pp.317-348.
- Nakamura, T. (2001), International Knowledge Spillovers and Technology Imports: Evidence from Japanese Chemical and Electric Equipment Industries, *Journal of the Japanese and International Economies*, 15, pp.271-297.
- Ray, A.S. and S. Bhaduri (2001), R&D and Technological Learning in Indian Industries: Econometric Estimation of the Research Production Function, *Oxford Development Studies*, 29, pp.155-171.
- Schive, C. (1995), Industrial Policies in a Maturing Taiwan Economy, *Journal of Industry Studies*, 2, pp.5-25.
- Tan, L.T. and A.R. Hwang (2002), Imported Technology and R&D in Taiwanese Electronic Industry, *Review of Development Economics*, 6, pp.77-90.
- Trajtenberg, M. (2001), Innovation in Israel, 1968-97: A Comparative Analysis Using Patent Data, *Research Policy*, 30, pp.363-389.
- Zhao, H. (1995), Technology Imports and Their Impacts on the Enhancement of China's Indigenous Technological Capability, *Journal of Development Studies*, 31, pp.585-602.